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Implications of Horizontal Symmetries on Baryon Number Violation in Supersymmetric Models

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The smallness of the quark and lepton parameters and the hierarchy between them could be the result of selection rules due to a horizontal symmetry broken by a small parameter. The same selection rules apply to baryon number violating terms. Consequently, the problem of baryon number violation in Supersymmetry may be solved naturally, without invoking any especially-designed extra symmetry. This mechanism is efficient enough even for low-scale flavor physics. Proton decay is likely to be dominated by the modes $K^+\bar{\nu}_i$ or $K^0\mu^+(e^+)$, and may proceed at observable rates.

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The smallness and the hierarchy in the quark and lepton parameters may be related to a horizontal symmetry $\mathcal{H}$ that acts on the fermions. Such a horizontal symmetry may be responsible for the hierarchy if it is explicitly broken by an operator in the Lagrangian whose coefficient is a small parameter λ. (Numerically, we expect $\lambda \sim 0.2$ to explain the Cabibbo angle.) The transformation laws of λ under $\mathcal{H}$ control the order in perturbation theory of the various elements in the fermion mass matrices ("selection rules") and, consequently, some parameters depend on powers of λ higher than others, namely a hierarchy can be generated.

Supersymmetric models allow, in general, baryon number and lepton number violation [1]. If the relevant couplings are of $\mathcal{O}(1)$, then proton decay and neutron-antineutron oscillations are predicted at unacceptably fast rates. One may try to solve this problem by invoking additional symmetries designed particularly to forbid the problematic terms [2]. (The problem may also be solved with specific gauge symmetries [3].) However, the selection rules due to the horizontal symmetry apply to baryon violating terms in the Lagrangian as well and are likely to suppress them. It is the purpose of this work to see whether this mechanism can naturally solve the problem of baryon number violation in supresymmetric theories. (A similar question has been recently taken in ref. [4].)

We work in the framework of supersymmetric Abelian horizontal symmetries that has been recently investigated in refs. [5] [6] [7]. (For recent related work, see [8].) We assume that the low energy spectrum consists of the fields of the minimal supersymmetric Standard Model with the following $SU(3)_C \times SU(2)_L \times U(1)_Y$ quantum numbers:

$$\begin{aligned} &Q_i(3,2)_{1/6},\ \bar{u}_i(\bar{3},1)_{-2/3},\ \bar{d}_i(\bar{3},1)_{1/3},\ L_i(1,2)_{-1/2},\ \bar{\ell}_i(1,1)_1,\\ &\phi_u(1,2)_{1/2},\ \phi_d(1,2)_{-1/2}, \end{aligned} \tag{1}$$

where $i = 1,2,3$ is a generation index. Each of these fields carries a charge under an Abelian horizontal symmetry $\mathcal{H}$. For most of our discussion, it makes no difference whether $\mathcal{H}$ is local or global, continuous or discrete. $\mathcal{H}$ is explicitly broken by a small parameter λ to which we attribute charge -1. Then, the following selection rules apply:

a. Terms in the superpotential that carry charge $n \geq 0$ under $\mathcal{H}$ are suppressed by $\mathcal{O}(\lambda^n)$, while those with $n < 0$ are forbidden due to the holomorphy of the superpotential. (If $\mathcal{H}$ is a discrete Z_N, the suppression is by $\mathcal{O}(\lambda^{n(\mathrm{mod} N)})$.)

b. Terms in the Kähler potential that carry charge n under $\mathcal{H}$ are suppressed by $\mathcal{O}(\lambda^{|n|})$ (or $\mathcal{O}(\lambda^{n(\mathrm{mod}N)})$ for $\mathcal{H} = Z_N$).

The resulting fermion mass matrices should give the following orders of magnitude for the various physical parameters (we assume $\tan\beta \sim 1$):

$$\begin{aligned} 1 &\sim m_t/\langle\phi_u\rangle, \\ \lambda &\sim |V_{us}|, \\ \lambda^2 &\sim |V_{cb}|,\ m_d/m_s,\ m_s/m_b,\ m_b/m_t,\ m_\mu/m_\tau, \\ \lambda^3 &\sim |V_{ub}|,\ m_u/m_c,\ m_c/m_t,\ m_e/m_\mu,\ m_\tau/m_t. \end{aligned} \tag{2}$$

Some of these order of magnitude estimates are ambiguous, *e.g.* $m_b/m_t \sim \lambda^3 - \lambda^2$. Furthermore, the estimates depend on the scale. Also, it could be that m_b/m_t is explained by large $\tan\beta$ and that the bare m_u vanishes. None of these points changes the principles of our mechanism, so we will only study models that satisfy the hierarchy as given in (2). It is straightforward to change the specific details of our examples to take account of other options.

The following terms are relevant to proton decay and neutron-antineutron oscillations (gauge indices are suppressed below):

(a) Dimension-4 terms from the superpotential:

$$\left[\lambda'_{ijk} L_i Q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k\right]_F . \tag{3}$$

(b) Dimension-5 terms from the superpotential:

$$\frac{1}{M}\left[\kappa'_{ijkl} Q_i Q_j Q_k L_l + \kappa''_{ijkl} \bar{u}_i \bar{u}_j \bar{d}_k \bar{\ell}_l\right]_F . \tag{4}$$

(c) Dimension-6 terms from the Kähler potential:

$$\frac{1}{M^2}\left[\rho'_{ijkl} \bar{u}_i^\dagger \bar{d}_j^\dagger Q_k L_l + \rho''_{ijkl} Q_i Q_j \bar{u}_k^\dagger \bar{\ell}_l^\dagger\right]_D . \tag{5}$$

There are also dimension-5 terms from the Kähler potential, as well as other terms of each of the three types given above. However, within our framework, these additional B or L violating terms never give the dominant contribution to the processes that we study.

When SUSY particles are integrated out, combinations of the above operators give effective B- and L-violating four-fermi operators of the general type $\eta_{\rm eff} qqq\ell$ (where generation, gauge and Lorentz indices are suppressed) that lead to proton decay. The upper bounds on proton decay rates [9] require $\eta_{\rm eff} \leq 10^{-32}\ GeV^{-2}$. This can be translated to the following bounds on the λ, κ and ρ couplings:

$$\frac{\lambda'_{ijk}\lambda''_{11k}}{M^2_{\rm SUSY}} \leq 10^{-32}\ GeV^{-2} \tag{6}$$

with $i=1,2,3,\ j=1,2,\ k=2,3$.

$$\begin{aligned} \frac{\kappa'_{112i}}{M_{\rm SUSY}M} &\leq 10^{-29}\ GeV^{-2}, \\ \frac{\kappa''_{1jkl}(K^u_{RR})_{1j}}{M_{\rm SUSY}M} &\leq 10^{-30}\ GeV^{-2}, \end{aligned} \tag{7}$$

with $i=1,2,3,\ j=2,3,\ k,l=1,2$. (We have taken $\frac{\alpha_2}{4\pi}\frac{m_{\tilde w}}{m_{\tilde q}} \sim 10^{-3}$ and $\frac{\alpha_3}{4\pi}\frac{m_{\tilde g}}{m_{\tilde q}} \sim 10^{-2}$. The K^q_{MN} mixing matrices for gaugino couplings are defined in [6].)

$$\begin{aligned} \frac{\rho'_{1ijk}}{M^2} &\leq 10^{-32}\ GeV^{-2}, \\ \frac{\rho''_{1l1m}}{M^2} &\leq 10^{-32}\ GeV^{-2}, \end{aligned} \tag{8}$$

with $(i,j)=(1,2),(2,1),(1,1),\ k=1,2,3,\ l,m=1,2$. If, for example, we take $M \sim \frac{M_p}{\sqrt{8\pi}} = 2.4\times 10^{18}\ GeV$ and $M_{\rm SUSY}\sim 10^3\ GeV$, then (6) and (7), expressed in powers of $\lambda=0.2$, become

$$\lambda'_{ijk}\lambda''_{11k} \leq \lambda^{37}, \tag{9}$$

$$\kappa'_{112i} \leq \lambda^{11},\ \ \kappa''_{1jkl}(K^u_{RR})_{1j} \leq \lambda^{12}, \tag{10}$$

while (8) allows $\rho = \mathcal{O}(1)$. If we assume squark degeneracy, $(K^u_{RR})_{12}=0$ and there is no constraint on κ''.

In principle, it is always possible to find a horizontal symmetry $\mathcal{H}$ that gives the required suppression of the B violating couplings. To see that, note that the Yukawa terms have an accidental symmetry $U(1)_B\times U(1)_L\times U(1)_X$ (under $U(1)_X$, ϕ_d carries charge -1, $\bar d_i$ and $\bar\ell_i$ carry charge $+1$, and all other fields are neutral). Therefore, requiring (2) fixes the horizontal charges only up to arbitrary shifts by $\alpha B+\beta L+\gamma X$. In ref. [5],

which was concerned with fermion mass matrices only, this symmetry of the Yukawa terms (together with the gauge $U(1)_Y$) was used to put the $\mathcal{H}$-charges of ϕ_u, ϕ_d, Q_3 and L_3 to zero. However, the B and L violating terms that we investigate here are *not* invariant under this symmetry. Thus we can always find a symmetry

$$\tilde{\mathcal{H}} \subset \mathcal{H} \times U(1)_B \times U(1)_L \times U(1)_X \tag{11}$$

that is *isomorphic* to $\mathcal{H}$ but will give an arbitrarily strong suppression of the $\Delta B \neq 0$ terms. The symmetry $\tilde{\mathcal{H}}$ will, of course, dictate precisely the same mass matrices as $\mathcal{H}$, but at the same time it will solve the baryon-number violation problem of Supersymmetry without invoking any additional ad-hoc symmetry. (Actually, as long as the only input from the lepton sector are the charged lepton masses, we have the freedom of $U(1)_e \times U(1)_\mu \times U(1)_\tau$ rather than just $U(1)_L$.)

The only potential drawback in this mechanism is that the required $\tilde{\mathcal{H}}$ charges may turn out to be very large, in which case the model becomes unnatural and is unlikely to be realized in nature. To make this point clear, $\tilde{\mathcal{H}} = \mathcal{H} + 100B$ (where $\mathcal{H}$ is the horizontal symmetry under which ϕ_u, ϕ_d, Q_3 and L_3 are neutral) would certainly satisfy all the constraints in (9) and (10). But when the various quark and lepton supermultiplets carry $\tilde{\mathcal{H}}$ charges of $\mathcal{O}(100)$ (in units of the $\tilde{\mathcal{H}}$-charge of λ), the model is not very plausible. The real test of this mechanism is then whether it can solve the baryon violation problem with reasonable charges, say ≤ 10. Below we give three examples to demonstrate that, indeed, rather simple horizontal symmetries with reasonable charges to all fields can suppress baryon number violation to an acceptable degree.

First, we take the "master model" of ref. [7]. The horizontal symmetry is $\mathcal{H} = U(1)_H$ with a small breaking parameter λ carrying $H = -1$. Consider the following set of charge assignments:

$$\begin{array}{ccccccccc} Q_1 & Q_2 & Q_3 & \bar{d}_1 & \bar{d}_2 & \bar{d}_3 & \bar{u}_1 & \bar{u}_2 & \bar{u}_3 \\ (3) & (2) & (0) & (9) & (8) & (8) & (3) & (1) & (0) \\ L_1 & L_2 & L_3 & \bar{\ell}_1 & \bar{\ell}_2 & \bar{\ell}_3 & \phi_u & \phi_d & \\ (7) & (7) & (7) & (7) & (4) & (2) & (0) & (-6). & \end{array} \tag{12}$$

It leads to the following fermion mass matrices:

$$M^d \sim \langle\phi_d\rangle \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^5 \\ \lambda^5 & \lambda^4 & \lambda^4 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}, \quad M^u \sim \langle\phi_u\rangle \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda & 1 \end{pmatrix}, \quad M^\ell \sim \langle\phi_d\rangle \begin{pmatrix} \lambda^8 & \lambda^5 & \lambda^3 \\ \lambda^8 & \lambda^5 & \lambda^3 \\ \lambda^8 & \lambda^5 & \lambda^3 \end{pmatrix}. \tag{13}$$

This gives the required order of magnitude estimates (2). At the same time, (12) leads to

$$\lambda'_{i23} \sim \lambda^{17}, \quad \lambda''_{113} \sim \lambda^{20}, \tag{14}$$

$$\kappa'_{112j} \sim \lambda^{15}, \tag{15}$$

which satisfy (9) and (10). (We assume here squark degeneracy so that κ'' poses no problem, and $M = \frac{M_p}{\sqrt{8\pi}}$ so that ρ' and ρ'' give negligible contributions.) The leading proton decay mode, due to $\lambda'_{i2j}\lambda''_{11j}$, is

$$p \to K^+\bar{\nu}_i. \tag{16}$$

One of the main purposes of refs. [5] and [7] was to check whether the flavor physics scale could be at low enough energy to be directly accessible in future experiments. The answer was that this is possible though not very likely. Now the following question arises: if we require that the horizontal symmetry solves the baryon number violation problem in the manner described above, is it still possible to have M as low as $\sim 10^5\ GeV$? (In the examples of a full high-energy theory in refs. [5][7], based on the model of ref. [10], M is the mass scale for heavy fermions in vector representations.) Assuming squark degeneracy, that would require

$$\lambda'_{ijk}\lambda''_{11k} \leq \lambda^{37}, \tag{17}$$

$$\kappa'_{112i} \leq \lambda^{30}, \tag{18}$$

$$\rho'_{112i},\ \rho''_{111j} \leq \lambda^{31}. \tag{19}$$

Had we found that this is possible only with very high $\mathcal{H}$-charges, we should have concluded that the ideas of low-energy flavor physics and of B-violation suppressed by $\mathcal{H}$ are mutually exclusive.

The models where a low scale could be consistent with FCNC and Landau poles constraints employed $\mathcal{H} = U(1)_{H_1} \times U(1)_{H_2}$. There are two small breaking parameters: $\lambda_1 \sim \lambda^2$ and $\lambda_2 \sim \lambda^3$ with (H_1, H_2) charges $(-1,0)$ and $(0,-1)$, respectively. Our second example is then a model with this horizontal symmetry and the following charge assignments:

$$\begin{array}{ccccccccc} Q_1 & Q_2 & Q_3 & \bar{d}_1 & \bar{d}_2 & \bar{d}_3 & \bar{u}_1 & \bar{u}_2 & \bar{u}_3 \\ (5,3) & (6,2) & (5,2) & (3,2) & (1,3) & (1,3) & (-5,-1) & (-6,-1) & (-5,-2) \\ L_1 & L_2 & L_3 & \bar{\ell}_1 & \bar{\ell}_2 & \bar{\ell}_3 & \phi_u & \phi_d & \\ (1,4) & (2,3) & (5,6) & (5,3) & (4,3) & (0,0) & (0,0) & (-5,-5). & \end{array} \tag{20}$$

It leads to the following fermion mass matrices:

$$\begin{gathered} M^d \sim \langle \phi_d \rangle \begin{pmatrix} \lambda_1^3 & \lambda_1\lambda_2 & \lambda_1\lambda_2 \\ 0 & \lambda_1^2 & \lambda_1^2 \\ 0 & \lambda_1 & \lambda_1 \end{pmatrix}, \quad M^u \sim \langle \phi_u \rangle \begin{pmatrix} \lambda_2^2 & 0 & \lambda_2 \\ \lambda_1\lambda_2 & \lambda_2 & \lambda_1 \\ \lambda_2 & 0 & 1 \end{pmatrix}, \\ M^\ell \sim \langle \phi_d \rangle \begin{pmatrix} \lambda_1\lambda_2^2 & \lambda_2^2 & 0 \\ \lambda_1^2\lambda_2 & \lambda_1\lambda_2 & 0 \\ \lambda_1^5\lambda_2^4 & \lambda_1^4\lambda_2^4 & \lambda_2 \end{pmatrix}. \end{gathered} \tag{21}$$

This gives the order of magnitude estimates (2). At the same time, (20) leads to

$$\lambda'_{223} \sim \lambda_1^9\lambda_2^8, \quad \lambda''_{113} = 0, \tag{22}$$

$$\kappa'_{1122} \sim \lambda_1^{18}\lambda_2^{11}, \tag{23}$$

$$\rho'_{1122} \sim \lambda_1^{10}\lambda_2^4, \quad \rho''_{1211} \sim \lambda_1^{11}\lambda_2^3, \tag{24}$$

which satisfy (17), (18) and (19). The vanishing of λ''_{113} comes from holomorphy and would be lifted if the symmetry is discrete. (We, again, assume here squark degeneracy so that κ'' poses no problem.) The leading proton decay mode, due to ρ''_{1211}, is

$$p \to K^0 \bar{e}^+. \tag{25}$$

As emphasized in ref. [4], this mode does not typically arise in SUSY GUT models and is likely to signify flavor physics of the type described in this work.

As our third example, we take the quark-squark alignment models of ref. [7]. This class of models gives a suppression of FCNC from supersymmetric diagrams by forcing

the quark mass matrices and squark mass-squared matrices to be simultaneously approximately diagonal [6]. No squark degeneracy is needed. The horizontal symmetry is $\mathcal{H} = U(1)_{H_1} \times U(1)_{H_2}$. There are two small breaking parameters, $\lambda_1 \sim \lambda$ and $\lambda_2 \sim \lambda^2$ with (H_1, H_2) charges $(-1, 0)$ and $(0, -1)$, respectively. Consider the following charge assignments:

$$\begin{array}{ccccccccc} Q_1 & Q_2 & Q_3 & \bar{d}_1 & \bar{d}_2 & \bar{d}_3 & \bar{u}_1 & \bar{u}_2 & \bar{u}_3 \\ (1,1) & (-2,2) & (-2,1) & (1,4) & (6,1) & (2,3) & (1,1) & (3,-1) & (2,-1) \\ L_1 & L_2 & L_3 & \bar{\ell}_1 & \bar{\ell}_2 & \bar{\ell}_3 & \phi_u & \phi_d & \\ (5,1) & (-1,4) & (1,3) & (-3,5) & (2,1) & (0,1) & (0,0) & (0,-3). & \end{array} \tag{26}$$

It leads to the following fermion mass matrices:

$$\begin{array}{ll} M^d \sim \langle \phi_d \rangle \begin{pmatrix} \lambda_1^2 \lambda_2^2 & 0 & \lambda_1^3 \lambda_2 \\ 0 & \lambda_1^4 & \lambda_2^2 \\ 0 & 0 & \lambda_2 \end{pmatrix}, & M^u \sim \langle \phi_u \rangle \begin{pmatrix} \lambda_1^2 \lambda_2^2 & \lambda_1^4 & \lambda_1^3 \\ 0 & \lambda_1 \lambda_2 & \lambda_2 \\ 0 & \lambda_1 & 1 \end{pmatrix}, \\ M^\ell \sim \langle \phi_d \rangle \begin{pmatrix} \lambda_1^2 \lambda_2^3 & 0 & 0 \\ 0 & \lambda_1 \lambda_2^2 & 0 \\ 0 & \lambda_1^3 \lambda_2 & \lambda_1 \lambda_2 \end{pmatrix}. & \end{array} \tag{27}$$

Note, in particular, the various zero entries in M^d which suppress the SUSY contribution to $K - \bar{K}$ mixing. The charge assignments (26) lead to

$$\lambda'_{323} \sim \lambda_1 \lambda_2^8, \quad \lambda''_{113} \sim \lambda_1^4 \lambda_2^8, \tag{28}$$

$$\kappa'_{1123} \sim \lambda_1 \lambda_2^7, \quad \kappa''_{1322} \sim \lambda_1^{11} \lambda_2^2, \quad (K^u_{RR})_{13} \sim \lambda_1 \lambda_2^2, \tag{29}$$

which satisfy (9) and (10). Note the need to consider $\kappa''_{1ijk}(K^u_{RR})_{1i}$ as squarks are not necessarily degenerate. (We, again, take $M = \frac{M_p}{\sqrt{8\pi}}$ so that ρ' and ρ'' give negligible contributions.) The leading decay mode, due to $\lambda'_{i23}\lambda''_{113}$, is

$$p \to K^+ \bar{\nu}_i. \tag{30}$$

The models presented above assume that there is no additional symmetry that forbids the B and L violating terms. It could be that there exists a discrete R-parity, R_p, which forbids the λ couplings of eq. (3), as well as dimension-5 D-terms. In this case, the only dangerous terms are the κ couplings of eq. (4) (and the ρ couplings of eq. (5), if the scale M is below 10^{16} GeV). This scenario was recently investigated in an interesting paper by

Murayama and Kaplan [4]. In our framework, this scenario makes the constraints much easier to satisfy. With degenerate squarks and $M = \frac{M_p}{\sqrt{8\pi}}$ (as assumed in [4]), the only important constraint is $\kappa'_{1jkl} \leq \lambda^{11}$ which is easily satisfied with small $\mathcal{H}$ charges, *e.g.*

$$\begin{array}{ccccccccc} Q_1 & Q_2 & Q_3 & \bar{d}_1 & \bar{d}_2 & \bar{d}_3 & \bar{u}_1 & \bar{u}_2 & \bar{u}_3 \\ (3) & (2) & (0) & (1) & (0) & (0) & (3) & (1) & (0) \\ L_1 & L_2 & L_3 & \bar{\ell}_1 & \bar{\ell}_2 & \bar{\ell}_3 & \phi_u & \phi_d & \\ (3) & (3) & (3) & (3) & (0) & (-2) & (0) & (2). & \end{array} \tag{31}$$

We have also investigated the constraints from $n-\bar{n}$ oscillations. When SUSY particles are integrated out, combinations of the operators under study give effective B-violating six-fermi operators of the general type $\sigma_{\text{eff}} qqqqqq$ (where generation, gauge and Lorentz indices are suppressed) that lead to neutron-antineutron oscillations. The upper bound on the rate of $n-\bar{n}$ oscillations [11] requires $\sigma_{\text{eff}} \leq 10^{-27}\ GeV^{-5}$. This gives, for example, the following bounds on λ'' [12]:

$$\begin{aligned} \frac{\lambda''_{112}\lambda''_{113}\lambda''_{323}\lambda''_{312}}{M^5_{\text{SUSY}}} &\leq 10^{-27}\ GeV^{-5}, \\ \frac{\lambda''_{112}\lambda''_{113}(K^d_{RR})_{12}(K^d_{RR})_{13}}{M^5_{\text{SUSY}}} &\leq 10^{-27}\ GeV^{-5}. \end{aligned} \tag{32}$$

We find, however, that these bounds are always satisfied once those from proton decay are.

To summarize the main conclusions of this work:

(a) Abelian horizontal symmetries that explain the smallness and hierarchy in the quark and lepton sector parameters, may at the same time suppress baryon number violating couplings to an acceptable degree. There is no need to invoke extra symmetries for the sole purpose of forbidding the $\Delta B \neq 0$ terms.

(b) For models of horizontal symmetries where a phenomenologically interesting scale for flavor physics is consistent with FCNC and Landau poles constraints, the constraints from proton decay and $n-\bar{n}$ oscillations can still be satisfied with the same low scale.

(c) Operators that do not contribute to proton decay when squarks are degenerate do contribute in models of quark–squark alignment but, again, can be satisfactorily suppressed by the horizontal symmetry.

(d) If the suppression of proton decay is due to a horizontal symmetry, then the leading decay modes are to final kaons, *i.e.* $K^+\bar{\nu}_i$ or $K^0\mu^+(e^+)$. In the absence of information

about neutrino masses and mixings, no analogous statement can be made about the final leptons.

(e) Unlike R_p which forbids certain terms, the horizontal symmetry could either forbid (F terms) or suppress them. Furthermore, the possibility of Supersymmetry without R-parity leads to many other interesting phenomenological consequences [13].

The fact that horizontal symmetries that are invoked to explain the hierarchy in fermion parameters may solve many other problems – FCNC in Supersymmetry [6], the μ-problem [7], hierarchy of symmetry breaking scales [7], the strong CP problem [14], FCNC due to light leptoquarks [15], and baryon number violation in Supersymmetry as described in [4] and in this work – makes this extension of the Standard Model a very attractive one.

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